Jérôme I. Mars* and James W. Rector, III, University of California, Berkeley

SUMMARY

Multichannel filtering for wavefield separation have been used in seismic processing for decades and have become an essential component in VSP and crosswell reflection imaging (Hardage, 1985, Rector, et al, 1995). The need for good multichannel wavefield separation filters is acute in borehole seismic imaging techniques such as VSP and crosswell reflection imaging, where strong interfering arrivals can temporally overlap with desired arrivals. For example, tube waves can be very strong in VSP and crosswell data. Tube waves can have similar frequency content to desired reflections making them difficult to temporally attenuate. Shear waves and conversions can also be an interference problem in many wide-angle imaging applications. In conventional surface seismic data, multichannel filtering prior to stacking is often less critical because there is often a time window where reflections and multiples can be isolated. In many land surveys, ground roll can be removed by low-cut filtering in the time domain.

INTRODUCTION

Previous work in VSP wavefield separation has focused on the algorithmic formulation of the wavefield separation filter and has emphasized removal of the direct arrival. Techniques such as median filter (Hardage, 1985), radon filters (Foster and Mosher, 1992) and optimal array filters (Seeman and Horowicz, 1983) have all been advocated and explored. In crosswell reflection imaging the volume of seismic data is often equivalent to 1000 offset VSP's (Rector, et al, 1995). The multiple domains available for processing (Common Receiver Gather - Common Source Gather - Common Midpoint Gather and Common Offset Gather) has dictated a more pragmatic approach in which domain selection (Rector, et al, 1994, Rowbotham and Goulty, 1994) and sequence development (Rector, et al 1995) have overshadowed the algorithmic formulation of the wavefield separation filter. Previous to our work, only simple mean, median filter, and f-k filters have been applied to separate crosswell reflections. In addition, crosswell reflection arrivals are often contaminated by many different arrivals including tube waves, shear conversions, multiples, direct arrival, guided waves, and therefore the multichannel filter formulations may vary with arrival type. Finally, the high frequencies present in many crosswell data (up to 2000 Hz in many cases) require very fine spatial sampling to avoid spatial aliasing. In many cases, cost considerations result in somewhat aliased data, further compounding the difficulty of wavefield separation.

DESCRIPTION OF MULTICHANNEL FILTERS

We tested two different types of multichannel filters on our crosswell data sets; Median filters and eigenvectors filters. Median filters are the most common type of filter used in wavefield separation of VSP data. They are typically formulated as pure spatial filters. When there is no amplitude variation in the wavefield, the median is identical to the mean and the filter impulse response is a sinc (k_X/N) where N is the length of the median filter. There are two important factors that make median filters attractive for wavefield

separation of VSP and crosswell data; first, median filters theoretically preserve step functions or strong discontinuities and therefore do not smear reflection arrivals past their termination at the direct arrival. Second, median filters are less sensitive to outliers than mean filters and in situations where there is high amplitude crossing interference, median filters can often attenuate the interference substantially. Furthermore, since median filters are less sensitive to outliers, the median filter is ideal to eliminating spike noise. The main problem with this formulation filter is that there is generally no frequency dependence in the filter.

The eigenvectors filter has recently become popular in some circles as wavefield separation technique for VSP and crosswell data (Freire and Ulrych, 1987), The eigenvectors of as particular gather that is a function of space time r(t,x) is obtained as follows:

1) The covariance matrix, M, is computed. Each column of the covariance matrix is simply the average of the adjacent trace cross-correlation functions. The basic idea of the covariance matrix is to enhance those arrivals that are large amplitude and are aligned or have linear moveout and, to attenuate those arrivals that are either very weak and/or have static shifts between traces.

2) The Singular Value Decomposition of M is computed, $M=U\Delta V^T$ where Δ is a diagonal matrix of eigenvalues, U is the matrix of eigenvectors of M, and V^T is the matrix of the eigenvectors of M^T.

3) Filtering is done by projecting the eigenvectors corresponding to a selected number of eigenvalues onto the original gather. The eigenvectors associated with the largest eigenvalues are the ones with the most linear moveout and/or have the largest amplitude components of the original gather.

Since the eigenvectors filter works on amplitude as well as moveout, it is not simply a spatial filter. A very high amplitude impulsive event would be still found in the first few eigenvectors, whereas this event would be smeared over the entire f-k plane and would not be separable with a spatial filter. Likewise, a strongly aliased large amplitude event would be found and possibly separable from the desired signal in the first few eigenvectors, whereas this event would be wrapped multiple time across the spatial Nyquist axis and would not be separable with a spatial filter.

Thus, eigenvectors can be thought as a filter that can attenuate large amplitude energy even when the energy has complex spatial characteristic. Eigenvectors filters may be useful in attenuating large amplitude aliased arrivals such as tube waves in crosswell data sets. One of the problems with the eigenvectors filters is its non deterministic, data dependent nature. We found that in data sets with signal-to-noise ratios that vary within a particular gather, the higher

eigenvectors of the gather often contain some components of desired signal as well as noise. From these observations, we developed a constrained eigenvectors filter, which cascades a spatial filter with the eigenvectors projection. By cascading a spatial filter on a top of the eigenvectors, we constrain the eigenvectors filter to only attenuate interference with undesired spatial characteristics.

COMPARISON OF MULTICHANNEL FILTER
PERFORMANCE ON AN ENTIRE CROSSWELL DATA SET.

To compare the performance of different multichannel filters on an entire crosswell data set, we used a data collected by TomoSeis Inc. using a piezoelectric source and hydrophone receivers between wells spaced 990 ft at British Petroleum's Devine Test Site. Previous crosswell studies performed at Devine site demonstrated the existence of high frequency energy and reflections from major stratigraphic boundaries (Harris et al, 1987, Miller, et al, 1992, Lazaratos, et al 1993, Schuster, et al, 1993). Anisotropy and large velocity contrast were shown to complicate the reflection imaging process.

Figure 1 is a representative common source gathers for this data set. Along with the P direct arrivals, the major interference consists of tube wave arrivals. S-waves and converted S-wave arrivals were very weak in this data set. The 5 ft sampling of sources and receivers created a data set that is substantially aliased. Tube waves in common source or receiver space cross the spatial Nyquist axis at a frequency of about 450 Hz, resulting in several wraps across the f-k_z plane in the band of interest (200 to 2,000 Hz). The well spacing of 990 ft is representative of a typical well spacing in U.S. Oil fields. The larger well spacing and the relatively limited vertical aperture of the survey created wide incidence angles, resulting in a direct arrival that were sometimes difficult to identify. We used a processing similar to the one used by Rector, et al, (1995), to extract upgoing P-wave reflections from this crosswell data set. However, we modified the sequence to remove upgoing and downgoing tube waves as well as the P-direct arrivals. We did not apply filtering on shear arrivals. We experimented with the different filters for the different arrivals, different filter parameters and different preprocessing. With respect to the preprocessing, we found that arrival alignment and scaling was necessary to substantially attenuate the undesired arrival. We picked and aligned both the P-direct arrivals and the tube waves prior to filtering.

Effect of arrival alignment and amplitude scaling

In figure 2, we see the common source gather of figure 1 in the f-k domain. We see very strong tube waves that wrap across the upgoing reflections (apparent velocity of about -20,000 ft/s) at a frequency of about 900 Hz for upgoing tube waves, and 1100 Hz for downgoing tube waves. The upgoing and downgoing tube waves wrap across the upgoing reflections again at about 1400 Hz and 1550 Hz, respectively.

Since the tube wave velocity varies highly with hole diameter and shear wave velocity (White, 1983), the apparent velocity of the tube wave is not exactly constant over the range of source depths. To correct, for the variable

tube wave velocity, we can align the tube wave prior to application of the multichannel filters. Alignment is well-known as an essential component in VSP and crosswell wavefield separation (Hardage 1985, Rector et al, 1995). After alignment and scaling, the tube wave arrival is concentrated in a narrower range of apparent velocities.

Comparison of multichannel filters

We compared the different filters by applying one type of filter (median, eigenvectors) for the entire wavefield separation sequence that consisted of 6 separate filters.

Figure 3 shows the data after aligning and filtering the upgoing and downgoing tube waves with a median filter. We see notches in the upgoing reflection spectrum crossing points. Similar results were obtained with the f-k and Radon filters (Embree, et al, 1963, Foster and Mosher, 1992). By contrast, the eigenvectors filter passes the reflection arrival in the overlapping frequency range. The tube wave noise has been attenuated without the notching effects of spatial filters (figure 4).

Due to the large amplitude difference between the tube waves and the upgoing reflection, the eigenvectors filter is able to work past the limits of aliasing. Unfortunately initial time-domain analysis of the eigenvectors-filtered results also showed that significant amounts of reflection energy were attenuated using the eigenvectors filter. When we reduced the percentage of energy removed by the eigenvectors filter, we began to see residual tube waves, indicating that some eigenvectors contain both undesired tube wave arrivals along with reflection arrivals. The eigenvectors filter was the only filter that was able to attenuate the tube waves without putting notches in the frequency spectrum of the upgoing P wave reflection. In summary, the eigenvectors filters also attenuated some of the stronger reflection arrivals. From these results, it became apparent that to avoid the effects of tube wave aliasing, we needed to implement an eigenvectors filter. However, to avoid removing some of the reflection energy of interest, we needed to 'constrain' the eigenvectors filter.

To attenuate only a constrained range of spatial frequencies, we constructed a constrained eigenvectors filter by the following process. First, we computed the eigen-image of the aligned tube waves. Then, we spatially filtered this eigen-image with a mild 3-trace mix. Finally we subtracted this mixed eigen-image from the original data. Figure 5 shows the result of the standard eigenvectors filters versus constrained eigenvectors filters. We see that reflections are clearer for the constrained eigenvectors filters than the standard eigenvectors filtered data.

Figure 6 shows an unprocessed common mid-depth gathers from the center of the survey (2,300 ft). The common mid-depth domain is a useful domain in which to identify reflections because for a constant velocity, the upgoing and downgoing reflection moveout are zero. A strong upgoing P-wave reflection from what we believe to be the base of the Austin Chalk is apparent in the unprocessed common mid-depth gathers.

Figure 7a shows the final wavefield separated data using a 9 trace median filter for every multichannel filtering operation. Figure 7b shows the data using the constrained

eigenvectors filter to attenuate the aliased tube waves and a radon filters to attenuate the unaliased direct arrivals. In these displays, it is difficult to identify which gather is superior. The median filtered results appear to produce reflection energy with a ringer appearance, possibly indicative of a loss of low frequency energy. We evaluated the signal quality of the filtered common mid depth gathers by stacking the data after correcting for the residual moveout computed along the large reflectors at 30 ms. Figure 8 shows the stacked spectrum. Note that the data from figure 7a have the most broad band spectrum. We can see the notches introduced by the pure spatial filtering to the tube waves at 950, 1,100 and 1500 Hz. We can see also the loss in low frequency produced by the median filter. From the stacked spectrum analysis, it appears that the choice of wavefield separation filter is quite important to the quality and post-separation bandwidth of the reflection energy.

CONCLUSIONS.
We have shown that the choice of the multichannel filter and filter parameters is critical to the wavefield separation of crosswell data. We found that spatial aliasing creates situations where the application of purely spatial filters will create notches in the frequency spectrum of the desired reflection arrival. Median filters exhibited the added problem of attenuating the lower frequencies of the desired signal. Eigenvectors filters were found to work past the limits of aliasing, but eigenvectors filters were found to be strongly dependent on the ratio of undesired to desired signal amplitude. For data, where the desired and undesired signals had comparably amplitude, the eigenvectors filters were not useful in wavefield separation. As a result of these observations, we developed a new type of multichannel filter that combined the best characteristics of spatial filters and eigenvectors filter. We term this filter a constrained eigenvectors filter. Results of the applying the constrained eigenvectors filter to the entire crosswell data set are superior to either the spatial or standard eigenvectors filter results.

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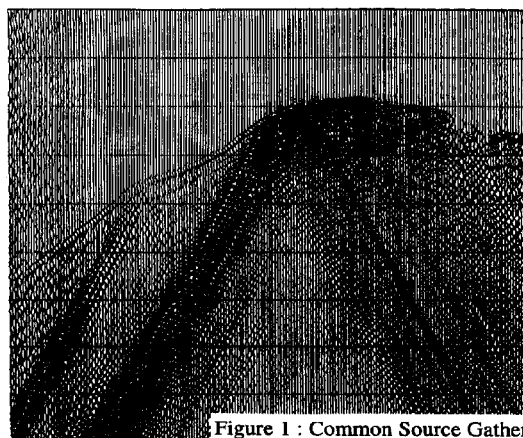WHITE, J. E., 1983, Underground Sound Application of Seismic Waves, Elsevier Publishers, Amsterdam.
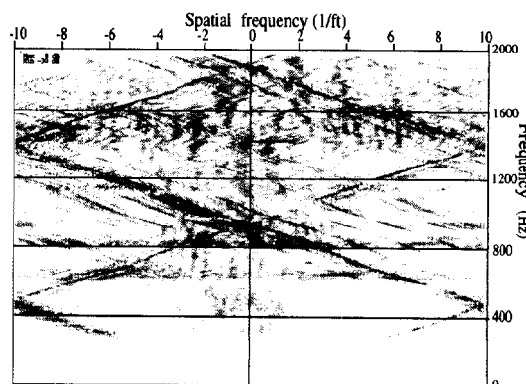

Figure 1 : Common Source Gather
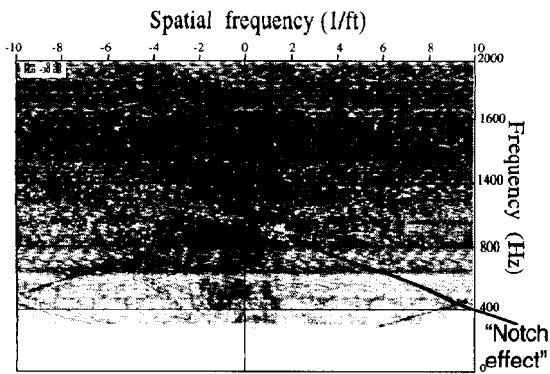

Figure 2 : FK Spectrum of initial data

Spatial frequency (1/ft)

Figure 3: F-K spectrum after removing upgoing
tube wave with median filter

Spatial frequency (1/ft)
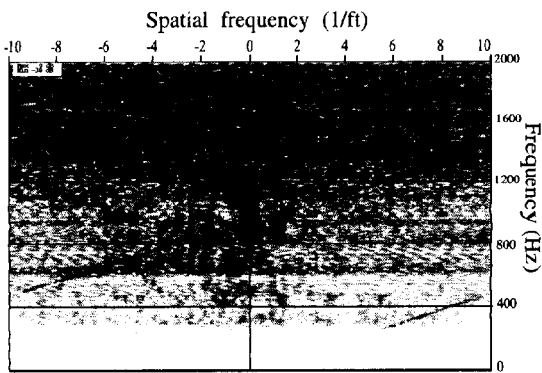
Figure 4 : F-K spectrum after removing upgoing tube
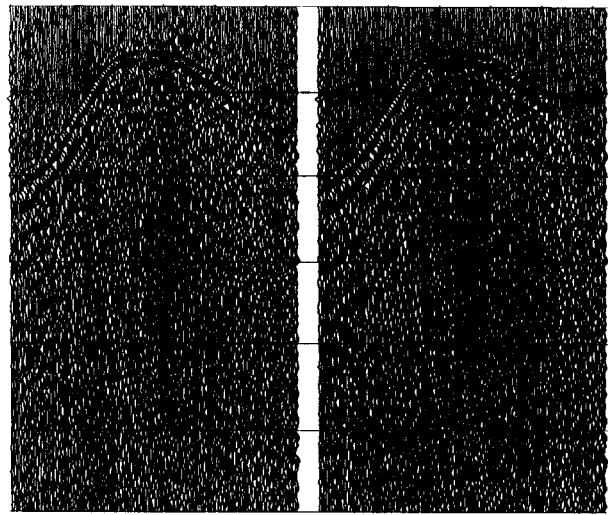wave by constrained eigenvectors filter

Figure 5 A : Results given by   Figure 5 B : Result given by
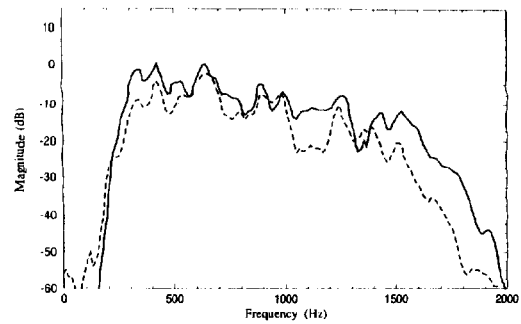Standard Eigenvectors Filter   Constrained Eigenvectors Filter

Figure 8 : Spectrum of stacked data.
Solid line   : Constrained Eigen. Filter
Dotted line : Median filter.
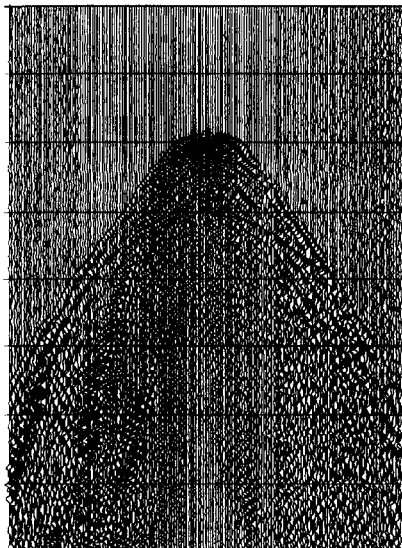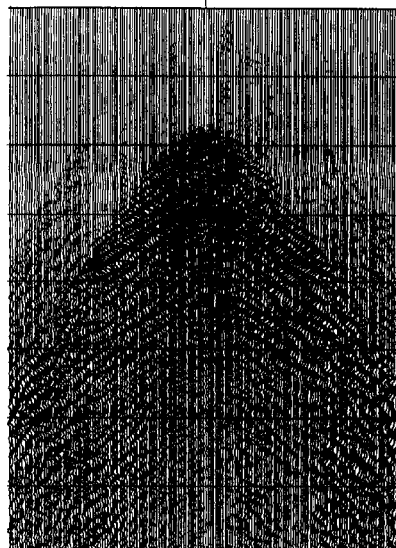
Figure 6 : Unprocessed Common   Figure 7 A : Common Mid-depth Gather   Figure 7 B : Common Mid-depth Gather
Mid-depth Gather   Processed by Median filters   Processed by Constrained Eigenvectors filter